11. Temperature-rise tests

A temperature-rise test is defined as a test to determine the temperature rise above ambient of one or more of the transformer's windings, as measured at the terminals. The result for a given terminal pair is the average value of the temperature of the entire circuit; it is not the temperature at any given point in a specific winding. The term "average temperature rise" refers to the value determined by measurements on a given terminal pair of the winding. It does not refer to the arithmetic average of results determined from different terminal pairs of the transformer.

See IEEE Std C57.12.00-2000, 4.1, for conditions under which temperature limits apply. All temperature rise tests shall be made under normal (or equivalent to normal) conditions of the means of cooling.

a) Temperature-rise tests shall be conducted on transformers filled to the proper liquid level.
b) The temperature-rise tests shall be made in a room that is as free from drafts as practicable.
c) When it is not possible, or not practical, to test the transformer as a completed assembly, then the transformer shall be tested with those components that are required to ensure that the normal means of cooling the transformer are met during the temperature-rise test.

11.1 Test methods

Tests shall be made by one of the following methods:

a) Actual loading
b) Simulated loading
   1) The short-circuit method, in which appropriate total losses are produced by the effect of short-circuit current
   2) The loading back (opposition) method, in which rated voltage and current are induced in the transformer under test

11.1.1 Actual loading

The actual loading method is the most accurate of all methods, but its energy requirements are excessive for large transformers.

Transformers of small output may be tested under actual load conditions by loading them on a rheostat, bank of lamps, water box, etc.

11.1.2 Simulated loading

11.1.2.1 Short-circuit method

a) Prior to making the Total Loss Run, measure load loss at rated current and frequency for the particular combination of connections and taps that give the highest average winding temperature rise. This will generally involve those connections and taps resulting in the highest losses. This thermal connection load loss shall be measured in accordance with Clause 9 of this standard and referenced to a temperature equal to rated average winding rise plus 20 °C. The required total losses for the Total Loss Run shall be the sum of thermal connection load loss plus no-load loss measured in accordance with Clause 8 of this standard.

b) **Total Loss Run:** Short-circuit one or more windings and circulate sufficient current at rated frequency to produce the required total losses as determined in step a).

c) Determine liquid temperature rises as described in 11.3.2.

d) **Rated Current Run:** Reduce the current in the windings to the rated value for the connection and the loading used. Hold the current constant for one hour. Measure the liquid temperatures and immediately shut down and measure the hot resistances in accordance with 11.2.2.

e) Repeat step d) for hot resistance measurements on additional terminal pairs if needed to meet the time limit criteria of 11.2.2.

f) Determine average winding rises in accordance with 11.3.3.

11.1.2.2 Loading back method

Duplicate transformers may be tested by connecting their respective high-voltage and low-voltage windings in parallel (see Figure 27 and Figure 28). Transformers shall be tested on the particular combination of connections and taps that give the highest average winding temperature rise. This will generally involve those connections and taps resulting in the highest losses.

a) Apply rated voltage at rated frequency to one set of windings. Circulate load current by opening the connections of either pair of windings at one point and impress a voltage across the break just sufficient to circulate rated current at rated frequency for the connection and loading used.

b) Measure liquid temperatures and determine liquid temperature rises as described in 11.3.2.

c) Immediately shut down and measure the hot resistance in accordance with 11.2.2.

d) When needed to meet the time limit criteria of 11.2.2, resume the heat run for one hour, holding rated voltage at rated frequency for the connection and loading used. Measure the liquid temperatures and immediately shut down and measure the hot resistance of additional terminal pairs in accordance with 11.2.2.

e) Determine average winding temperature rises in accordance with 11.3.3.

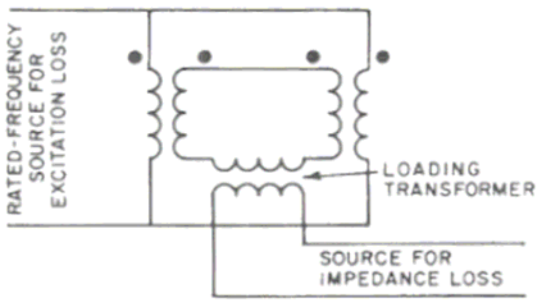


Figure 27—Example of loading back method: Single phase

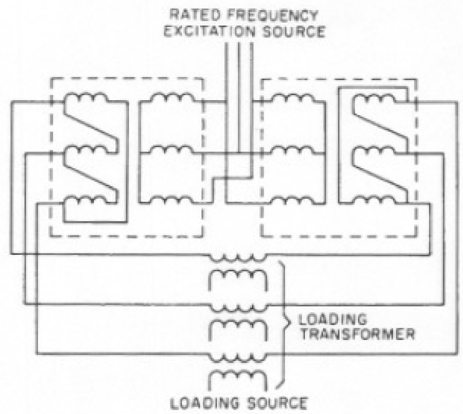


Figure 28—Example of loading back method: Three phase

11.2 Resistance measurements

11.2.1 Cold-resistance measurements

Cold-resistance measurements shall be taken on all terminal pairs in accordance with Clause 5. The same test equipment shall be used for both cold-resistance and hot-resistance measurements. Normally, cold-resistance measurements are taken prior to loading the transformer for temperature rise test. However, it is permissible to allow the transformer to cool to ambient temperature and perform cold-resistance measurements after the loading test. Whenever it is necessary to make cold-resistance measurements following the temperature rise test, the cool down time shall be sufficient to allow the criteria in 5.1 to be met.

11.2.2 Hot-resistance measurements

When the transformer is shut down for hot-resistance measurements, fans and cooling water shall be shut off. Oil pumps may be shut off or left running during shut down. Hot-resistance measurements shall be taken as soon as possible after shut down, allowing sufficient time for the inductive effects to disappear as indicated from the cold-resistance measurement. To minimize inductive effects when transferring measuring instrument leads from one terminal-pair to another, the same relative polarity should be maintained between measuring leads and transformer terminals.

a) The time from instant of shutdown shall be recorded for each resistance measurement, and

b) At least one resistance measurement shall be taken on all terminal pairs within 4 min after shutdown, and

c) A series of at least four resistance measurements shall be made on one terminal pair corresponding to a phase of a winding, and

d) Resistance-time measurements in accordance with c) shall be made on all windings, and

e) The resistance-time data collected in c) shall be corrected to the instant of shutdown using a resistance-time cooling curve determined by plotting data on suitable coordinate paper, or by using a curve fitting program, and

f) The resistance-time data obtained on one phase of a winding shall be used to determine the correction to shutdown for the other phases of the same winding, provided the first measurement on each of the other phases has been taken within 4 min after shutdown.

Curve accuracy (enough data points to be statistically significant): See Attachment B.

11.3 Temperature measurements

11.3.1 Ambient temperature measurements

11.3.1.1 Air-cooled transformers

For air-cooled transformers, the ambient temperature shall be taken as that of the surrounding air, which should not be less than 10 °C nor more than 40 °C. For temperatures within this range, no correction factor shall be applied. Tests may be made at temperatures outside this range when suitable correction factors are available.

The temperature of the surrounding air shall be determined by at least three thermocouples or thermometers in containers spaced uniformly around the transformer under test. They shall be located at about half the height of the transformer and at a distance of one meter to two meters from the transformer. They shall be protected from drafts and radiant heat from the transformer under test or other sources.

When the liquid time constant of the transformer as calculated according to IEEE Std C57.91-1995, equation 14, is two hours or less, the time constant of the containers shall be between 50% and 150% of that of the transformer under test. When the liquid time constant of the transformer under test is more than 2 hours, the time constant of the containers shall be within one hour of the liquid time constant of the transformer under test.

The time constant of the containers shall be taken as the time necessary for its temperature to change 6.3 °C when the ambient temperature is abruptly changed 10 °C.

11.3.1.2 Water-cooled transformers

For water-cooled transformers, the flow rate in liters per minute and the temperature of the incoming and outgoing water shall be measured.

The ambient temperature shall be taken as that of the incoming water that should not be less than 20 °C nor more than 30 °C. For temperatures within this range, no correction factor shall be applied. Tests may be made at temperatures outside this range when suitable correction factors are available.

11.3.2 Liquid temperature rise determination

a) Liquid temperature rise is the difference between liquid temperature and the ambient temperature. The ultimate liquid temperature rise above ambient shall be considered to be reached when the top liquid temperature rise does not vary more than 2.5% or 1°C, whichever is greater, during a consecutive 3-hour period.

   It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, etc.

b) The top liquid temperature shall be measured by a thermocouple or suitable thermometer immersed approximately fifty millimeters below the top liquid surface.

c) The bottom liquid temperature shall be measured by one of the following methods
   1) Thermocouples may be attached to an insulated rod and located inside the tank so that the thermocouples are in the liquid flow path from the external cooling means to the bottom of the windings. Exercise caution when employing this method. This method may not be safe for transformers with very high voltage windings.
   2) If heat exchangers or radiators are mounted on a common manifold with a single entrance to the tank, the thermocouples may be located in the piping of the single entrance.
   3) If heat exchangers or radiators have multiple entrances into the tank, thermocouples may be installed in the bottom of one radiator or heat exchanger. For accuracy, a radiator or heat exchanger located in the middle of the bank is preferred.
   4) If it is not possible to measure the temperature of the liquid inside the tank, radiators, or heat exchangers, surface temperature measurements may be utilized with the results corrected to account for the temperature difference between the surface and the liquid inside the tank. If surface temperature measurements are made on radiator headers, choose headers one-third or one-half the way in from either end of a bank of radiators. For transformers without radiators, locate the thermocouples on the tank wall at the elevation of the bottom of the winding. Thermocouples located on external cooling surfaces, for the purpose of determining internal oil temperatures, shall be shielded and insulated so that their readings are not significantly affected by the air movement from fans or thermally induced air currents.

d) The average liquid temperature shall be determined as equal to top liquid temperature minus half the difference in temperature of the moving liquid at the top and bottom of the cooling means. When bottom liquid temperature cannot be measured directly, the temperature difference may be taken as difference between the surface temperature of the liquid inlet and outlet.

e) A thermocouple is the preferred method of measuring surface temperature (see 11.3.4 for method of measurement). Infrared measurement devices may also be used to measure surface temperatures, provided that such devices are calibrated to compensate for the temperature difference between the tank surface and inside liquid.

11.3.3 Average winding temperature-rise determination

The average winding temperature of a terminal pair corresponding to a winding phase shall be determined from the terminal pair's hot-resistance at shut down. When the determination of the hot-resistance is not possible (for example, with extremely low-resistance windings) other methods may be used. The average winding temperature of a terminal pair shall be determined by the following equation (26):

$$\theta_w = \frac{R_h}{R_c}(\theta_k + \theta_{rc}) - \theta_k \quad (26)$$

The average temperature rise of a terminal pair corresponding to a winding phase shall be determined by the following equation (27):

$$\Delta\theta_w = \Delta\theta_l + \theta_w - \theta_l \quad (27)$$

where

$\Delta\theta_w$ is the average winding temperature rise of a terminal pair, °C
$\Delta\theta_l = \theta_{l,TL} - \theta_a$ is the liquid temperature rise as determined from the total loss run, °C
θ_w is the average winding temperature of a terminal pair corresponding to hot resistance R_h, °C
$\theta_{l,TL}$ is the liquid temperature at end of total loss run
θ_l is the liquid temperature at shutdown
θ_a is the ambient temperature, °C
θ_{rc} is the temperature at which cold resistance R_c was measured, °C
R_c is the cold resistance, measured according to Clause 5 of this standard, (Ω)
R_h is the hot resistance of a terminal pair, (Ω)
θ_k is 234.5 °C for copper, and 225.0 °C for aluminum

NOTE—The value for θ_k may be as high as 230 °C for alloyed aluminum.

Average winding rise shall be calculated by using either top liquid rise or average liquid rise. When other than rated winding current is used, the average liquid rise method shall be used to determine winding rises.

a) In the top liquid rise method, the average winding temperature rise is equal to the top liquid rise, measured during the total loss run, plus the quantity (average winding temperature at shut down minus top liquid temperature at shut down).
b) In the average liquid rise method, the average winding temperature rise is the average liquid rise, measured during the total loss run, plus the quantity (average winding temperature at shut down minus average liquid temperature at shut down).

The average winding temperature rise for each terminal pair corresponding to a winding phase shall be corrected for actual test currents, test losses, and altitude as prescribed in 11.4. The corrected average winding temperature rise shall be reported for each terminal pair of the transformer.

11.3.4 Other temperature measurements

When measured, the temperature rise of metal parts other than windings shall be determined by use of a thermocouple, suitable thermometer, fiber optic temperature sensor, or other appropriate temperature measurement techniques.

A thermocouple is the preferred method of measuring surface temperature. When used for this purpose, the thermocouple should be soldered to the surface. When this is not practical, the thermocouple should be soldered to a thin metal plate or foil approximately 625 mm^2. The plate should be held firmly and snugly against the surface. The thermocouple should be thoroughly insulated thermally from the surrounding medium.

The surface temperature of metal parts surrounding or adjacent to outlet leads or terminals carrying heavy current may be measured at intervals or immediately after shut down.

11.4 Correction of temperature rise test results

For any of the loading methods adopted, temperature rise test results shall be corrected for the predictable effects caused by

a) difference in winding rated current and the winding test current,
b) difference in required loss and test loss, and
c) difference in altitude of operation.

11.4.1 Correction for differences between winding rated current and test current

When test equipment limitations dictate, it is permissible to hold winding current at a value lower than rated current for the winding, but not less than 85% of rated winding current. When the current held in any of the windings under test differs from the rated current, the observed differences between the average winding temperature at shut down and the average liquid temperature at shut down shall be corrected to give the average temperature rise of the windings at the rated current by using the following equation (28):

$$\Delta\theta_{w,c} = \Delta\theta_{w,o}\left(\frac{\text{rated current}}{\text{test current}}\right)^{2m} \qquad (28)$$

where

$\Delta\theta_{w,c}$ is the corrected difference between average winding temperature, corrected to shut down, and the average liquid temperature at shut down,
$\Delta\theta_{w,o}$ is the observed difference between average winding temperature, corrected to shut down, and the average liquid temperature at shut down, and
0.8 for Class ONAN, ONAF, OFAF and OFWF, and
1.0 for ODAF and ODWF.

The corrected average winding rise is the average liquid rise plus $\Delta\theta_{w,c}$.

11.4.2 Correction of liquid temperature rise for differences in required total loss and actual loss

This method may be used when actual loss is within 20% of the required total loss.

$$\Delta\theta_{l,c} = \Delta\theta_{l,o}\left[\left(\frac{P_r}{P_T}\right)^n - 1\right] \qquad (29)$$

where

$\Delta\theta_{l,c}$ is the liquid temperature rise correction, °C

$\Delta\theta_{l,o}$ is the observed liquid temperature rise, °C

P_r is the required total loss, W

P_T is the actual test total loss, W

n is 0.8 for Class ONAN,
is 0.9 for Class ONAF, OFAF or OFWF, and
is 1.0 for Class ODAF and ODWF.

Corrected liquid temperature rise = observed liquid temperature rise + $\Delta\theta_{l,c}$

Corrected average winding temperature rise = observed winding temperature rise + $\Delta\theta_{l,c}$

11.4.3 Correction of liquid temperature rises for differences in altitude

When tests are made at an altitude of 1000 m or less, no altitude correction shall be applied to the temperature rises.

When a transformer tested at an altitude of less than 1000 m is to be operated at an altitude above 1000 m, it shall be assumed that the liquid temperature rise will increase in accordance with the following equation (30):

$$\Delta\theta_A = \Delta\theta_o\left(\frac{A}{A_o} - 1\right)F \qquad (30)$$

where

$\Delta\theta_A$ is the increase in liquid temperature rise at altitude A meters, °C

$\Delta\theta_o$ is the observed liquid temperature rise, °C

A is altitude, m

A_0 is 1000 m

F is 0.04 for self-cooled mode, and 0.06 for forced-air-cooled mode.

NOTE—Winding temperature rise above liquid temperature is not affected by altitude.

END

ATTACHMENT A

New Business
By Subhash Tuli – Waukesha Electric Systems

To: Paulette Payne Powell
Working Group Temperature Rise Test Section 11.0 of C57.12.90

Often, a Temperature Rise Test is performed with constant current (I_{TC}) starting with Top Oil rise near Ambient temperature v/s accelerated constant watts with tap(s) position giving the highest average winding temperature rise and Oil rise (usually maximum total loss tap position) to simulate total losses at load current (I_L) based on pre specified load per equations 1,2 & 3 for calculating I_{TC} per C57.119 to obtain thermal constants such as, oil and each windings time constants and exponents.

$$I_{TC} = I_{L} \cdot \sqrt{[(\text{Cu losses} + \text{Fe losses}/\text{Cu losses})]}$$

Copper losses corrected for reference temperature (75 or 85°C) and Core losses Corrected to 20°C.

Once top oil temperature has stabilized (i.e. change in top oil temperature rise above ambient is less than 2.5% or 1°C in a time period, whichever is greater during a consecutive 3 hours period), data such as total losses, voltage and current, top oil, bottom oil, ambient temperature, temperatures of winding and Oil gauges etc, are recorded.

I have found on several occasions that the actual measured losses at the time of oil stability to be 10 – 15% higher than the actual calculated total losses (Cu losses + Fe losses) out of which I_{TC} was initially calculated, when the test began as measured losses have increased due to transformer heating and thus true Top oil temperature rise is affected and therefore should be corrected for the change in total losses from starting total loss per the equation for temperature correction in C57.12.90, equation # 28 and page 53:

$$T_d = T_b \left[(W/w)^n - 1 \right].$$

Where:

T_d = liquid rise correction (°C)
T_b = observed liquid rise (°C)
W= required loss (Watts)
w = actual loss (Watts)
n = 0.8 for ONAN, 0.9 for ONAF and OFAF, and 1.0 for ODAF.

If the Thermal tests are made with constant loss for top oil rise then there should not be any issue. If at the end of oil rise period or even prior to three hours of oil rise period, if the winding current is less than rated current heat run test must be performed with at least at rated current for top oil rise and winding rises.

Subhash Tuli
10/23/05
Revised 2/24/06

ATTACHMENT A

"Tom Harbaugh"
<tharbaugh@patransformer.com>

12/06/2005 09:18 AM

To: "Paulette Payne" papayne@pepco.com

Subject: Temperature Test new business

Hello Paulette,

I do not have Subhash's Email address and it probably is more appropriate that I respond to you anyway regarding the question he raised. Please feel free to forward it to Subhash if you feel it is appropriate.

Subash asked whether to adjust top oil rise due to a change in watts during oil temperature stability vs. calculated watts prior to the temperature test. This is an issue that I too have discussed with customer witnesses in the past.

Clause 11.5.2.1 states "Short-circuit one or more windings and circulate sufficient current at rated frequency to produce total losses for the connection and loading used. Total losses shall be those measured with clauses 8 and 9 of this standard and converted to a temperature equal to the rated average winding temperature rise plus 20°C".

*** **The purpose for the temperature rise test is to determine the maximum winding rises at rated (or customer specified) current and voltage**.*** Transformer nameplates provide no reference to watts - just amps and volts, and I don't believe any user loads transformers by monitoring watts.

The question is asked "Do I monitor and hold calculated losses, or do I monitor and hold a calculated current, to obtain oil temperature stability?". Why would a temperature test be conducted loading by watts???

The problem with calculating the watts to a temperature equal to the rated average winding temperature rise plus 20°C is that this presupposes the windings will rise to that temperature during the heat run. We all know that there can be significant variation, for many reasons, that can cause the windings to be at a much different temperature and thus the watts will be much different! Monitoring watts is not the way the test should be conducted!

Recognizing that fact (and in keeping with the intent of the temperature test) temperature tests should be loaded by monitoring and holding compensated rated current (ignoring watts!). Compensate the current by increasing it to account for the core losses (there could be a discussion on what temperature basis should be used to calculate core losses to compensate the load current). This method takes all uncertainty out of the question about adjusting rises based on watts variability and is more in line with the intent of the temperature test.

Tom Harbaugh
PTTI QA/Test Manager

ATTACHMENT B

Paulette Payne Powell
PEPCO

Ref: PC57.12.90.D2
11.2.2, "Hot Resistance Measurements'

Paulette:

Please note my suggestions with respect the above Clause and the defining of the cooling curve. It is my impression that the concerns among many of the WG members is that use of the cooling curve method has become arbitrary with respect to the length of time allowed for the curve and the accuracy of the results so obtained.

We should keep in mind that the use of the cooling curve method is a method based on fitting a series of resistance measurements that are changing non-linearly over the time period during which the measurements are taken. The regression curve produced from the best-fit yields the value of the resistance at time zero or the instant of shutdown. Since the analysis is based on a statistical method, the size of the sample or the number of data points has an impact on the accuracy of the curve and the results of the Temperature Rise of the Windings. In my opinion, if one is going to use a cooling curve, then 4 samples are not enough to establish an accurate curve. On the other hand, "hundreds" of points measured over a long time offer no significant increase in the prediction of the temperatures given the other variables present in the test process.

In an effort to attempt to resolve this concern, I submit the following:

a) The time from instant of shutdown shall be recorded for each resistance measurement, and
b) At least one resistance measurement shall be taken on all windings under test within 4 min after shutdown, and
c) A series of at least four resistance measurements shall be made on all windings under test. Each winding of the same phase shall conform to the ***cooling curve*** format requiring additional data points. These windings will be used as the basis for correction to time zero for the remaining windings tested, and
d) Resistance –time measurements in accordance with c) shall be made on all windings, and
e) The resistance-time data collected in c) shall be corrected to the instant of shutdown using a resistance-time cooling curve determined by plotting the data on suitable coordinate paper, or by using a computerized curve fitting program.
f) The ***cooling curve*** format shall consist of a minimum time range from zero to 10 minutes. All resistance measurements taken under 4 minutes will be recorded at no longer than 15-second intervals. All resistance measurements taken after 4 minutes will be recorded at 30-second intervals up to the 10-minute mark.
g) The resistance-time data obtained with the cooling curve can be used to determine the correction to shutdown for the same winding of the other phases, provided the first measurement on each of the other phases has been taken within 4 minutes after shutdown.

Respectfully submitted,

Robert G. Ganser, PE

ATTACHMENT C

Thermal Calculations - BLUME Method - barry Beaster

ATTACHMENT C

Thermal Calculations - BLUME Method - barry Beaster

WINDING	HV

R_{COLD} =	0.5674	Ω
T_{COLD} =	30	°C
$T_{AMBIENT}$ =	27.5	°C

Tinf =	63.024	°C
Rinf =	0.63824	Ω

Time (min)	R_{HOT} =		Blume	Fitted
1.50		Ω		
2.00		Ω		
2.50	0.6568	Ω	-3.98690	0.65660
3.00	0.6557	Ω	-4.04800	0.65563
3.50	0.6547	Ω	-4.10699	0.65470
4.00	0.6538	Ω	-4.16323	0.65383
4.50	0.6529	Ω	-4.22282	0.65300
5.00	0.6522	Ω	-4.27176	0.65222
5.50	0.6514	Ω	-4.33079	0.65148
6.00	0.6507	Ω	-4.38546	0.65078
6.50	0.6501	Ω	-4.43482	0.65011
7.00	0.6495	Ω	-4.48675	0.64948
7.50	0.6489	Ω	-4.54152	0.64889
8.00	0.6483	Ω	-4.59947	0.64832
8.50	0.6478	Ω	-4.65046	0.64779
9.00	0.6473	Ω	-4.70420	0.64728
9.50	0.6468	Ω	-4.76098	0.64680
10.00	0.6464	Ω	-4.80885	0.64635
10.50		Ω		
11.00		Ω		
11.50		Ω		
12.00		Ω		

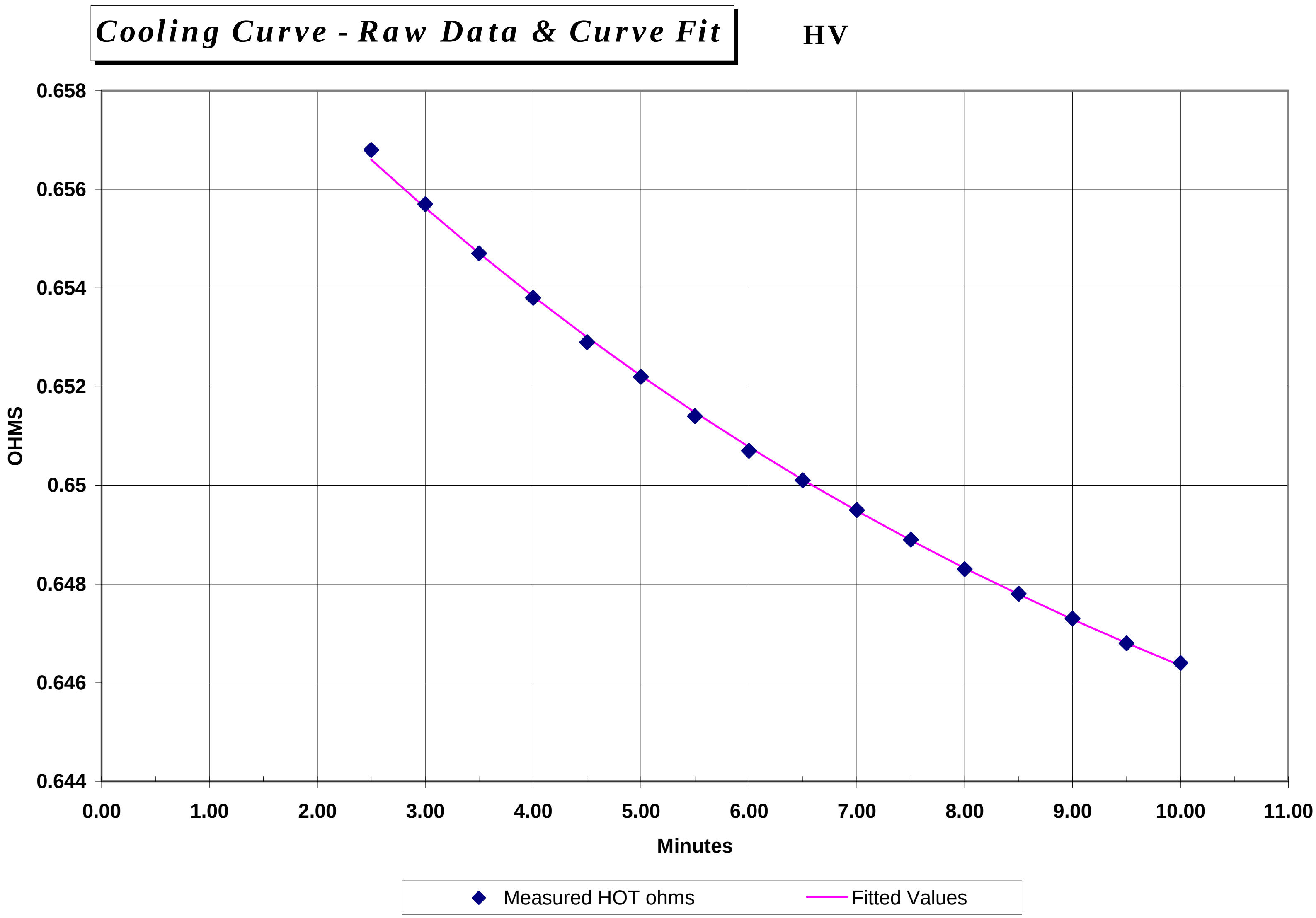
$R_{t=0}$ =	0.66235	Ω
θAVE =	74.26	°C
θRISE =	46.76	°C

Click to Solve

-3.7253	= Intercept
-0.1090	= Slope
0.9997	= R^2
0.0003	= 1.0 - R^2

ATTACHMENT C

Thermal Calculations - BLUME Method - *barry Beaster*



ATTACHMENT D
DRAFT

PCS REVISIONS TO C57.12.90

Task force for Resistance measurements (Clause 5 of C57.12.90)

Proposed Changes to Section 5

5. Resistance measurements

Resistance measurements are of fundamental importance for the following purposes:
a) Calculation of the I^2R component of conductor losses
b) Calculation of winding temperatures at the end of a temperature test
c) As a quality control test of the manufacturing process
d) As a base for assessing possible damage in the field

5.1 Determination of cold temperature

The cold temperature of the winding shall be determined as accurately as possible when measuring the cold
resistance. The precautions in 5.1.1 through 5.1.3 shall be observed.

5.1.1 General

Cold resistance measurements shall not be made on a transformer when ~~it is located in drafts or when it is located in a room in which~~ the liquid or winding temperature is fluctuating rapidly.

5.1.2 Transformer windings immersed in insulating liquid

The temperature of the windings shall be assumed to be the same as the average temperature of the insulating
liquid, provided
a) The windings have been under insulating liquid with no excitation and with no current in the windings
from 3 h to 8 h (depending upon the size of the transformer) for a transformer without pumps and for 1 h for transformer with pumps running before the cold resistance is measured.
b) The temperature of the insulating liquid has stabilized, and the difference between top and bottom
temperature does not exceed 5°C.

5.1.3 Transformer windings out of insulating liquid

The temperature of the windings shall be recorded as the average of several thermometers or thermocouples
inserted between the coils, with care used to see that their measuring points are as nearly as possible in
actual contact with the winding conductors. It should not be assumed that the windings are at the same
temperature as the surrounding air.

5.2 Conversion of resistance measurements

Cold winding resistance measurements are normally converted to a standard reference temperature equal to the rated average winding temperature rise plus 20°C. In addition, it may be necessary to convert the resistance measurements to the temperature at which the impedance loss measurements were made. The conversions are accomplished by Equation (1).

$$R_s = R_m \frac{T_s + T_k}{T_m + T_k}$$

(1)

where
*R*s is resistance at desired temperature *T*s,
*R*m is measured resistance,
*R*s is desired reference temperature (°C),
*T*m is the temperature at which resistance was measured (°C),
*T*k is 234.5°C (copper) or 225°C (aluminum).
NOTE—The value of *T*k may be as high as 230 °C for alloyed aluminum.

5.3 Resistance measurement methods

5.3.1 Voltmeter-ammeter method

The voltmeter-ammeter method is the most common method used for transformer winding resistance measurement. It should be employed only if the rated current of the transformer winding is 1 A or more. Resistance measuring systems employing computer controlled digital voltmeters, current measuring shunts, and/or digital ammeters of appropriate accuracy are commonly used for cold resistance measurements and in connection with temperature-rise determinations.

To use this method, the following steps should be taken:

a) Measurement is made with direct current, and simultaneous readings of current and voltage are taken using the connections of Figure 1. The required resistance is calculated from the readings in accordance with Ohm's Law. Electronic switching power supplies are generally used as voltage sources, however batteries or filtered rectifiers may also be used, especially in those instances where less ripple is desired in the measurement. Automatic recording of periodic voltage and current or resistance readings is recommended so that the pattern of resistance readings can be established. This pattern can then be analyzed to determine the resistance parameters for the test.

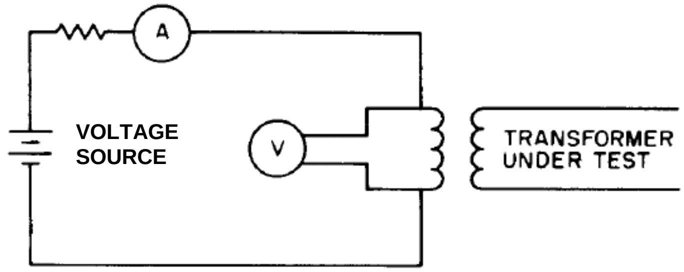


Figure 1—Connections for voltmeter-ammeter method of resistance measurement

b) The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This is to avoid including in the reading the resistances of current-carrying leads and their contacts and of extra lengths of leads.

d) Resistance is recommended to be measured at intervals of 5-10 seconds and the readings used shall be after the current and voltage have reached steady-state values.
When measuring the cold resistance, preparatory to making a heat run, note the time required for the readings to become constant. That period of time should be allowed to elapse before taking the

first reading when final winding hot resistance measurements are being made. The residual flux in the core should be made the same for both the cold and hot resistance measurements by saturating the core with dc current prior to the measurement.
In general, the winding will exhibit a long dc time constant. To reduce the time required for the current to reach its steady-state value, a noninductive external resistor may be added in series with the dc source. The resistance should be large compared to the inductance of the winding. It will then be necessary to increase the source voltage to compensate for the voltage drop in the series resistor. The time will also be reduced by ~~operating all other transformer windings open-circuited~~ passing a dc current through other windings in either the same polarity as the winding being tested for windings on the same phase or opposite polarity for other phases during these tests. For delta-connected windings, the time can also be reduced by opening the delta connection.

e) It is recommended that at ten or more readings, but a minimum of four readings shall be used for each cold resistance measurement and the average of the resistances calculated from these measurements shall be considered to be the resistance of the circuit. ~~Readings shall be taken with not less than four values of current when deflecting instruments are used.~~ For hot resistance readings, it is recommended that the individual readings are recorded every 5-10 seconds from the point where the inductive effect has subsided for at least 5 minutes (minimum of 30 readings). In no case should less than eight readings be used.
The current used shall not exceed 15% of the rated current of the winding whose resistance is to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.
c) When making manual resistance measurements:

1) to minimize errors of observation the measuring instruments shall have ranges that will give reasonably large deflection.

~~2) The polarity of the core magnetization shall be kept constant during all resistance readings.~~

~~NOTE—A reversal in magnetization of the core can change the time constant and result in erroneous readings.~~

2) To protect the voltmeter from injury by off-scale deflections, the voltmeter should be disconnected
from the circuit before switching the current on or off. To protect test personnel from inductive kick, the current should be switched off by a suitably insulated switch.
~~If the drop of voltage is less than 1 V, a potentiometer or millivoltmeter shall be used.~~
3) Due to inaccuracy of deflecting ammeters and voltmeters, current shunts and digital voltmeters or high-accuracy digital ammeters or other high accuracy instrumentation should be used that meets the requirement of ANSI Std. C57.12.00.

5.3.2 Bridge method

Bridge methods or other high-accuracy digital instruments should be used in cases where the rated current of the transformer winding to be measured is less than 1 A. NOTE—For resistance values of 1Ω or more, a Wheatstone Bridge (or equivalent) is commonly used; for values less than 1Ω, a Kelvin Bridge (or equivalent) is commonly used. Some modern resistance bridges have capability in both ranges.

5.4 Resistance measurement connections and reporting

The individual phase or terminal to terminal resistance readings should be reported along with the sum total winding resistance.

5.4.1 Wye Windings

For wye windings, the reported resistance measurement may be from terminal to terminal or from terminal to neutral. For the reported total winding resistance, the resistance of the lead from the neutral connection to the neutral bushing may be excluded.

5.4.1 Delta Windings

For delta windings, the reported resistance measurement may be from terminal to terminal with the delta closed or from terminal to terminal with the delta open to obtain the individual phase readings. The reported total winding resistance is the sum of the three phase readings if the delta is open. If the delta is closed, the reported total winding resistance is the sum of the three phase-to-phase readings times 1.5.

5.4.1 Autotransformer Windings

For autotransformer series winding resistance, the current shall be circulated between the HV and neutral terminals and the voltage measured between the HV terminal and the LV terminal. For the common winding resistance, the current shall be circulated between the HV and neutral terminals and the voltage measured between the LV and neutral terminals. For the resistance of the lead and in-line windings (if any) between the neutral connection and the LV terminal, the current shall be applied between the HV terminal and the LV terminal and the voltage measured between the LV terminal and the neutral terminal.

ATTACHMENT E
DRAFT

Proposed Change to C57.12.90/D2 12 April 2002

As we discussed during the Oct meeting of the task force, I have written a proposed change to the wording of 11.1.2.1 e).

The issue is that if all of the required hot resistance readings are not completed in the allowed time, the transformer must be heated again before performing another shutdown and continuing the resistance readings. Now the clause states that d) shall be repeated, which implies that the heating should be for 1 hour. If the liquid temperature does not return to the value of the first shutdown, then the measured resistances need to be corrected for the difference in the liquid temperature, adding another step of complexity, and another source for errors.

Proposal:

Existing wording

11.1.2.1

d) **Rated Current Run:** Reduce the current in the windings to the rated value for the connection and the loading used. Hold the current constant for one hour. Measure the liquid temperatures and immediately shut down and measure the hot resistances in accordance with 11.2.2.
e) Repeat step d) for not resistance measurements on additional terminal pairs if needed to meet the time limit criteria of 11.2.2.

Proposed wording [retain d), revise e)]:

11.1.2.1

d) **Rated Current Run:** Reduce the current in the windings to the rated value for the connection and the loading used. Hold the current constant for one hour. Measure the liquid temperatures and immediately shut down and measure the hot resistances in accordance with 11.2.2.
e) If some of the required hot resistance measurements cannot be completed during the time limit criteria of 11.2.2 the liquid must be brought back to the original test temperature before making any additional hot resistance measurements on the remaining terminal pairs. Repeat the application of the rated current value for the connection and the loading used and hold until the liquid temperature returns to the value measured in step d). Then proceed to complete the hot resistance measurements in accordance with 11.2.2, repeating this step as needed.

Don Platts March 2, 2006